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INDUCED STAR FORMATION IN INTERACTING GALAXIES

R.C. Kennicutt and K.A. Roettiger, Dept. of Astronomy, University of Minnesota

W.C. Keel, Sterrewacht Leiden

J.M. van der Hulst, Netherlands Foundation for Radio Astronomy

E. Hummel, Max-Planck-Institut für Radioastronomie

ABSTRACT. We have used measurements of H-alpha emission-line fluxes and FIR fluxes in ~100 interacting spirals to investigate the effects of close tidal interactions on the disk and nuclear star formation rates in galaxies. Two samples of interacting spirals were studied, a complete sample of close pairs, and a set of strongly perturbed systems from the Arp atlas. Both the integrated H-alpha luminosities and FIR luminosities are enhanced in the interacting galaxies, indicating that the encounters indeed trigger massive star formation in many cases. The response of individual galaxies is highly variable, however. A majority of the interacting spirals exhibit normal star formation rates, while a small fraction are undergoing bursts with luminosities which are rarely, if ever, observed in noninteracting systems. Virtually all of the latter are in the Arp sample, indicating that the Arp atlas is heavily biased to the most active star forming systems.

INTRODUCTION

Although it is well known that many of the most spectacular examples of starburst galaxies are members of interacting systems, relatively little quantitative information is available on the effects of interactions overall on the star formation properties of galaxies. The few available prior studies have yielded contradictory results. For example, comparisons of optical colors and infrared fluxes of normal and interacting galaxies by Larson and Tinsley (1978) and Lonsdale et al. (1984), respectively, provided evidence for strong interaction-induced star formation bursts, while Hummel's (1981) study of radio emission in close pairs revealed no evidence of abnormal disk star formation.

Here we report preliminary results from a new optical and infrared study of the star formation properties of interacting spiral and irregular galaxies. We have obtained measurements of the Hα line emission and (IRAS) far-infrared fluxes for objectively-defined samples of interacting and isolated galaxies, in order to quantitatively assess the effects of interactions on the global star formation rate. The results summarized here are part of a more general survey of the effects of interactions on the disk and nuclear properties of galaxies. Results on the nuclear activity have been published previously (Kennicutt and Keel 1984, Keel et al. 1985). We also refer the reader to closely related papers by Bushouse and Cutri elsewhere in this volume.

MATERIALS AND METHODS

Following our earlier study of nuclear activity (Keel et al. 1985), we have studied two samples of interacting galaxies. We used an unpublished catalog of galaxy pairs by T. van Albada, along with published redshift catalogs, to generate a magnitude-limited sample of 53 galaxies with close companions, selected independently of any abnormalities in structure, surface brightness, or star formation activity. While this sample (referred to hereafter as the complete pairs sample) may be contaminated by a few projected, noninteracting pairs, it is free of the potentially severe selection bias which may plague any sample which is selected according to purely morphological criteria. In order to assess the importance of this bias, and to explore the effects of unusually strong interactions, we also studied a subsample of pairs from the Arp (1966) Atlas of Peculiar Galaxies. This latter sample of 58 galaxies, including several members of the complete sample above, will be referred to hereafter as the "Arp" sample.

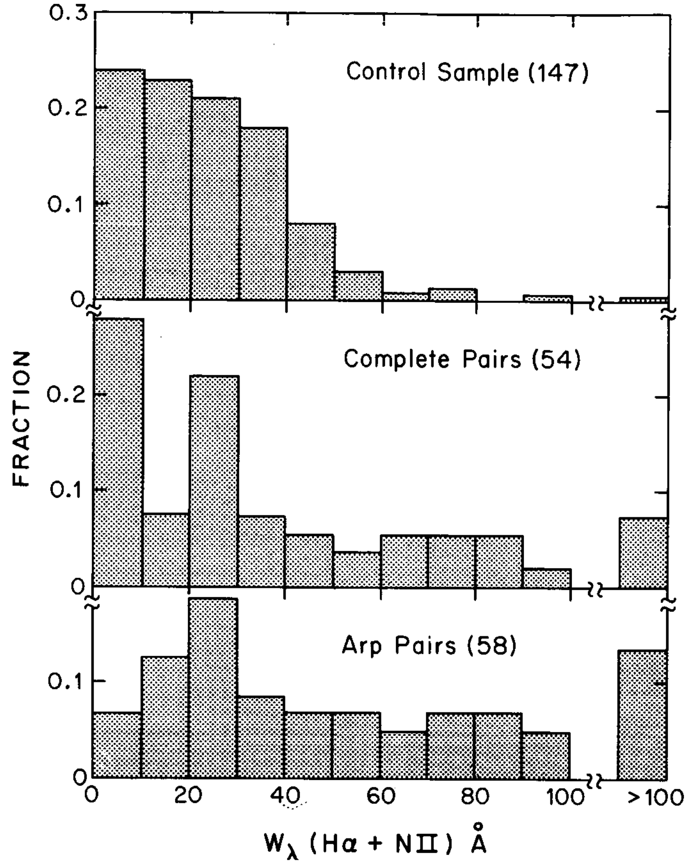
For comparison we used two control samples of noninteracting galaxies. For comparisons of Hα properties we used the survey of Kennicutt and Kent (1983), excluding elliptical and S0 galaxies, interacting systems, and Virgo cluster members. For the comparison of infrared properties we used in addition the magnitude-limited sample of Keel (1983), again excluding interacting galaxies. Both control samples exhibit very similar Hα and FIR properties.

We chose as our primary star formation indicator the integrated emission in the Hα emission line; this has proven to be a useful and sensitive tracer of the massive star formation rate (e.g., Kennicutt 1983, Gallagher et al. 1984). Digital images in Hα and in the red continuum were obtained during 1983-1985 on the 2.1m telescope at Kitt Peak National Observatory, using the ISIT Video Camera (53 galaxies), and a TI CCD direct camera (27 galaxies). The images were processed at KPNO to produce continuum-subtracted Hα + [NII] maps, as well as a normalized continuum frame of each galaxy. Final processing of the data, including sky background removal and simulated aperture photometry, was performed on the University of Minnesota image processing system. The main parameter of interest for this study is the integrated emission-line equivalent width of each galaxy, which is directly measurable from the relative fluxes in the net Hα and normalized continuum frames (and the bandwidth of the Hα filter). For data taken under photometric conditions we also derived the absolute emission line fluxes of the galaxies.

We also obtained photoelectric Hα and continuum aperture photometry for 27 galaxies, using the Schmidt Two-Holer photometer on the UM/UCSD 1.5m telescope on Mt. Lemmon. This provided a check on the equivalent widths derived from the imagery, as well as flux calibration data for images obtained on non-photometric nights. Comparison of the independent measurements indicates that the equivalent widths are accurate to ±5Å or better (or ±10% in galaxies with very high equivalent widths). Finally aperture photometry for a few nearby, large-diameter systems was taken from the surveys of Kennicutt and Kent (1983) and Kennicutt, Edgar, and Hodge (in preparation).

We have also used the IRAS 60μ and 100μ data to measure the integrated far-infrared (FIR) luminosities of the same galaxies. Roughly 30-40% of the galaxies in the control samples and in the complete pairs sample are larger than the IRAS detector resolution, so we determined integrated fluxes from the HCON1 sky flux maps, using a background-subtracting aperture photometry program on the University of Minnesota image processing system. Comparison of the derived fluxes with the IRAS Point Source Catalog (1985) fluxes for small faint galaxies in our program showed agreement to better than 15-25% on average, adequate for our purposes. For galaxies smaller than 4' diameter we used the PSC fluxes

Figure 1: Distribution of H-alpha emission equivalent widths in the interacting galaxy and control samples. Numbers in parentheses refer to the number of galaxies in each sample.



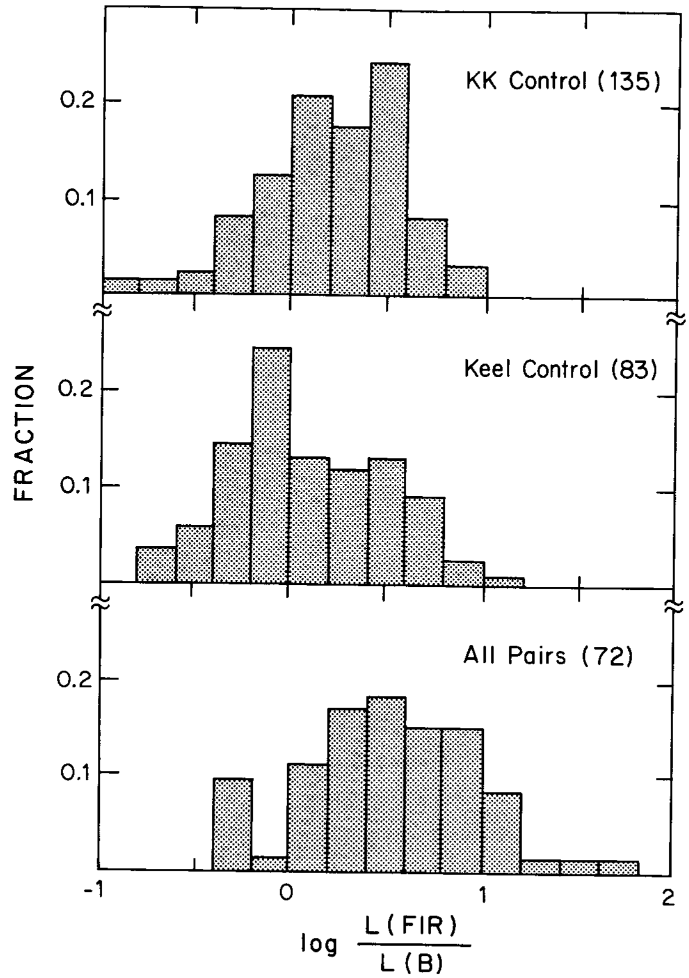
directly. Detection rates, using either the PSC or the sky flux maps, were 90% for the control samples, 85% for the complete pairs, and 75% for the Arp pairs. Unfortunately the IRAS survey does not resolve the emission from many of the close pairs; this is especially a problem for the Arp pairs. We obtained flux co-added maps for the close pairs in our samples, but in most cases the emission from the individual members is hopelessly blended. For the statistical comparisons which follow (only!), we have used the relative Hα fluxes of the individual components in the IRAS-blended pairs to estimate the relative FIR contribution of each member. Alternatively one can throw out the blended pairs altogether, or compare pairs together instead of individual galaxies, and the qualitative conclusions are unchanged.

The 60μ and 100μ fluxes were combined using the algorithm in the IRAS Explanatory Supplement (1985) to obtain an estimate of the integrated FIR flux for each galaxy. Finally, we normalized this FIR flux to the blue flux (the latter taken from de Vaucouleurs et al. 1976), in order to obtain a luminosity-free index of relative FIR emission in each galaxy.

RESULTS

Both samples of interacting galaxies exhibit significant enhancements in total Hα emission and FIR emission on average. Figures 1-2 show the distributions of integrated Hα + [NII] equivalent width and L(FIR)/L(B) in the samples of interacting and isolated galaxies. Both quantities vary systematically with Hubble type, so it is best to compare the different samples on a type-by-type

Figure 2: Distribution of the ratio of far-infrared to blue luminosity in the samples. The top two samples are the control samples as described in the text. The bottom is the combined interacting galaxy sample (complete and Arp).



basis, as is shown in Table 1 (also see Figs. 3-4). The distributions of morphological type in the three samples are very similar, however, so the type-averaged distributions shown in Figs. 1-2 can be directly compared.

Although the average levels of emission are significantly higher in interacting galaxies -- the average Hα equivalent widths and L(FIR)/L(B) ratios are both roughly a factor of two higher in the Arp sample than in the control samples -- the response of individual galaxies varies enormously. A large fraction of the interacting galaxies we studied, in fact, exhibit little or no enhancements in emission. In our complete sample, which should be the most representative of galaxies with close companions, the median emission levels are virtually identical to the control samples (though a few extreme starbursting systems are certainly evident). Virtually all of the starburst galaxies in the complete pairs sample are members of the Arp atlas. In contrast to the objectively-selected complete sample, the sample of galaxies selected solely on the basis of morphological peculiarity possesses, perhaps not surprisingly, a very high fraction of abnormally star forming systems, and a systematically high level of star formation overall. Clearly the star formation properties of a sample of interacting galaxies can be as dependent on the observational selection criteria as on the physical effects of the interactions themselves.

Figure 3: Same as Fig. 1, but showing only the early-type spirals. Note the broad dispersion in emission properties of the interacting galaxies.

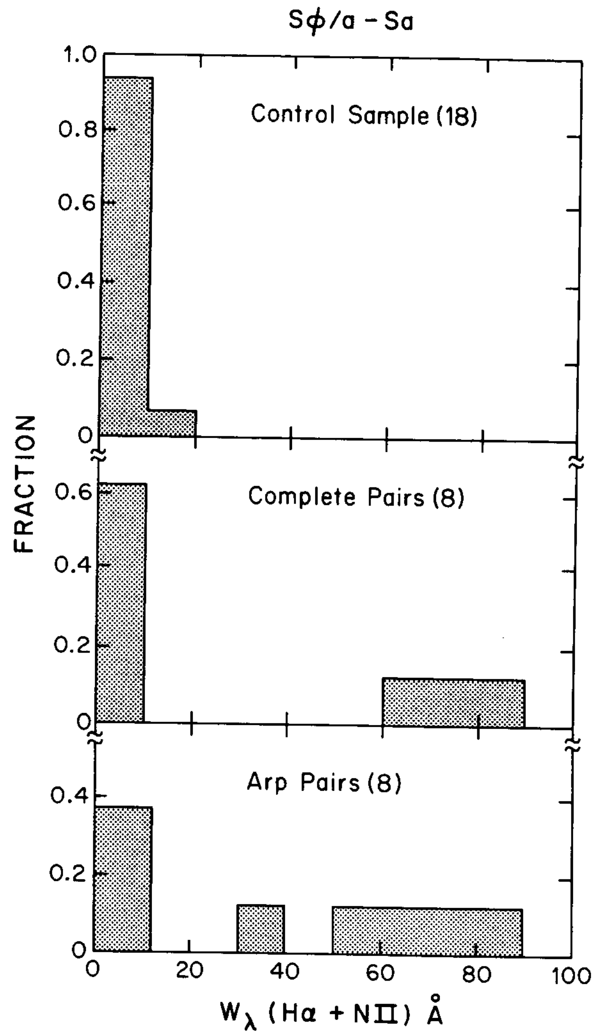


Table 1
MEDIAN EMISSION PROPERTIES

	Control Sample	Complete Pairs	Arp Pairs
W_λ(Hα + [NII]) (Å)			
All Types	22	24	46
S0/a-Sa	2	4	45
Sab-Sb	10	10	28
Sbc-Scd	26	32	33
Sm-Im	37	125	110
log (FIR/B) (detection only)			
All Types	+0.23	+0.44	+0.66
S0/a-Sa	-0.24	+0.42	+0.78
Sab-Sbc	+0.16	+0.29	+0.90
Sbc-Scd	+0.32	+0.43	+0.52
Sm-Im	+0.42	+0.78	+0.67

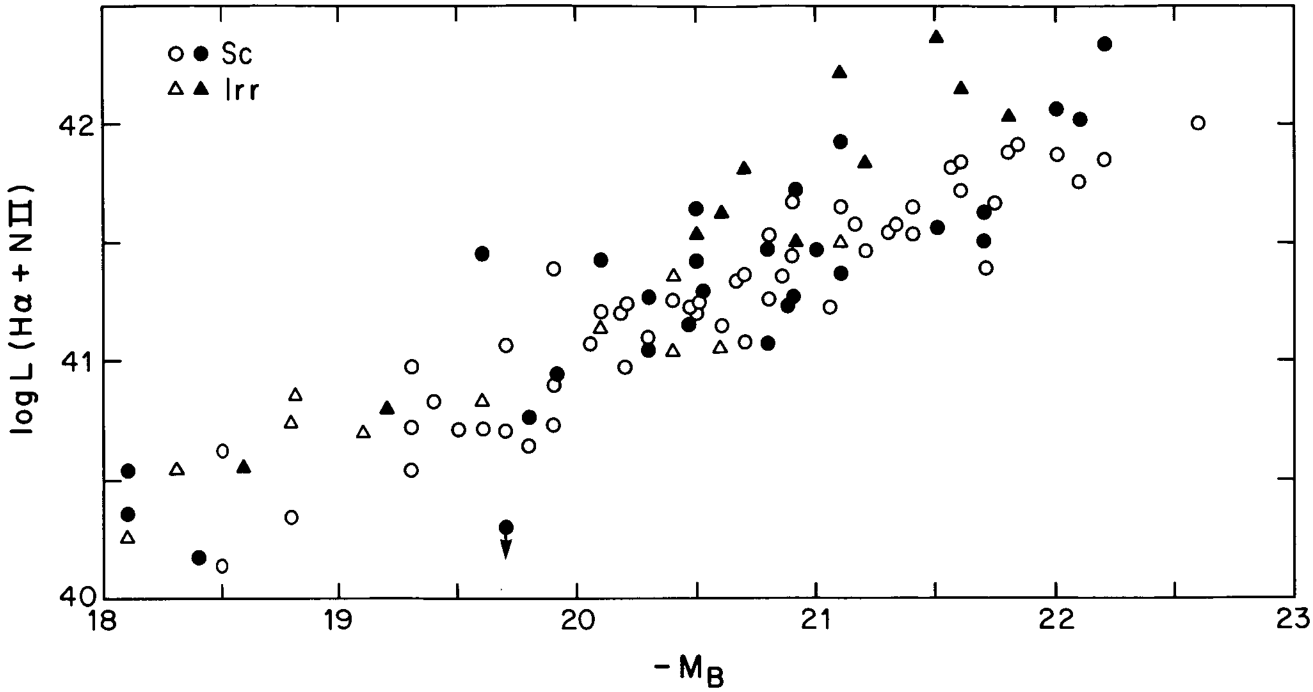


Figure 4: H-alpha luminosities for late-type galaxies. Closed symbols denote interacting galaxies, while open symbols denote galaxies in the control sample.

The emission properties of the galaxies illustrated in Figs. 1-2 appear to be continuous, but this is partly due to the mixing of different galaxy types. When we examine the distributions among galaxies of a fixed type, we observe a broader relative dispersion in properties, and in some cases a suggestion of bimodality in response. This is most clearly seen in the early-type spirals, as illustrated in Fig. 3. Isolated Sa galaxies normally exhibit only weak (if any) detectable Hα emission, indicative of a low massive star formation rate. Among the interacting Sa galaxies, however, we find both systems with normal (i.e., low) Hα equivalent widths, and several systems with emission levels which are abnormally high even for a late-type galaxy. In some cases this abnormally strong emission is primarily nuclear, in others it is primarily from disk emission, and in many both the disk and nuclear emission are enhanced.

For most of the galaxies we also have measured the total emission luminosities, and Fig. 4 illustrates the Hα properties of the late-type (Sc-Irr) galaxies in our study. On average the interacting galaxies exhibit stronger emission at all luminosities. The brightest systems, mostly members of the Arp sample, possess total Hα luminosities which are rarely if ever observed among isolated galaxies. Hence it is probably not surprising that such a large fraction of the luminous sources in the IRAS survey, Markarian catalogs, emission-line surveys, etc., are members of interacting systems.

DISCUSSION

The integrated Hα emission of a galaxy primarily measures the present star formation rate for massive (>10 $M_\odot$) stars, and hence our results confirm the hypothesis that close galaxy-galaxy interactions can induce bursts of star formation in spiral and irregular galaxies. The degree of enhancement in the star formation rate varies over a large range, from galaxies which appear to be unaltered by the interaction (at least as observed at present) to galaxies with star formation bursts which are 10-100 times stronger than is typically observed in isolated systems.

Our results explain what had been an apparent inconsistency between the studies of Larson and Tinsley (1978) and Lonsdale et al. (1984), who had found evidence for strong star formation bursts in interacting galaxies, and the study of Hummel (1981), who found no evidence for increased disk star formation in his complete sample of galaxy pairs. We confirm the results of all 3 studies. For strongly interacting, peculiar galaxies selected from sources such as the Arp atlas, including those which made up the bulk of the Larson and Tinsley and Lonsdale et al. samples, we observe systematically high star formation rates. Bushouse (1986) has observed a sample of even more strongly perturbed systems and observes even higher average star formation rates. On the other hand, for our objectively-selected complete sample of galaxies with close companions, we observe a slight increase in the average star formation rate, confirming Hummel's conclusion.

What can we learn from this complicated set of results? Clearly galaxy-galaxy interactions are capable of inducing star formation in galactic disks, and under special conditions can trigger major star formation bursts of a magnitude which is rarely if ever observed in noninteracting galaxies. Such starbursts are rare, however. The enhancement in star formation activity must be very sensitive to the ambient conditions in the disks of the galaxies, as well as to the orbital properties of the interaction itself.

The high star formation rates in the Arp sample confirm the not-surprising result that the most strongly disturbed galaxies exhibit the strongest star formation bursts. It is also, likely, however, that catalogs such as the Arp atlas are strongly biased toward unusually luminous, high surface brightness systems, and will a priori exhibit abnormal star formation properties. The relatively normal emission in most of the members of our complete sample of close pairs suggests that while induced star formation in strongly interacting galaxies may be a very important physical process for understanding the IRAS source counts, statistics of active and starbursting galaxies, etc., it is probably not a major influence on the current evolution of most galaxies, even those with nearly companions.

Several important questions remain to be explored in more detail. We intend to use our imagery to study the spatial distribution of the star formation in the interacting galaxies, and in particular to study the relative enhancements in disk and near-nuclear star formation. Preliminary analysis of our data indicates that the bulk of the Hα emission in most of the galaxies originates from star formation in the disk, but that the fraction of emission from the nucleus (or from a near-nuclear disk) is significantly higher than in isolated galaxies (see also Keel et al. 1985 and especially Bushouse 1986). We are also measuring the properties of individual HII regions in the galaxies, in order to better understand the nature of the induced star formation. A better understanding of the physical origins of the star formation, however, and its wide diversity in different systems, will probably require detailed spatially-resolved kinematic observations and modelling of individual systems.

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DISCUSSION

C. Magri: From your complete pairs sample, we see that proximity doesn't guarantee enhanced star formation in component galaxies. Have you found any discriminant (e.g., rotation velocity, HI content) of 'active' pairs vs. 'normal' pairs?

R. Kennicutt: It is very difficult to discern such second-order effects in our data, because the dispersion in emission properties among isolated galaxies is so large. Among the early-type spirals, we do notice that the 'active' galaxies often exhibit unusually strong nuclear emission.

M. Harwit: Since gas-gas interactions can be far more abrupt than stellar interactions in colliding galaxies, does one ever see galaxies in which the gas is clearly interacting, while the stellar components appear virtually unaffected?

R. Kennicutt: I do not think that enough data are available on gas distributions in galaxies to test your hypothesis. Most HI mapping studies of interacting galaxies, for example, are limited to pairs which show optical peculiarities. On the other hand, HI maps of a number of close groups (by M. Haynes, for example) do show prominent gaseous plumes among what are relatively undistorted galaxies in the stellar component.